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ORIGINAL ARTICLE

Interacting modified QCD ghost scalar field models of dark energy

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Abstract The interacting framework of modified QCD ghost dark energy with cold dark matter is being considered for illustrating the accelerated expansion of the universe. We develop the Hubble parameter numerically and find that it shows increasing behavior which is consistent with the present observations. Also, the equation state parameter shows evolution of the universe from matter dominated universe towards phantom era by evolving the quintessence as well as vacuum eras of the universe. The dynamics of scalar field and corresponding potential of various scalar field models shows consistence behavior with the accelerated expansion phenomenon. Also, the kinetic energy term of k-essence and dilaton models lies within the range where equation of state parameter represents the accelerated expansion of the universe.

Keywords QCD ghost dark energy · Cold dark matter · Scalar field models

1 Introduction

Dark Energy (DE) is one of the fascinating phenomenon which cause accelerated expansion of the universe. This phenomenon has been confirmed through various observational data (Riess et al. 1998; Perlmutter et al. 1999). The DE is the mysterious form of force which contains repulsive behavior, but its nature is still unknown. The cosmological constant is the pioneer candidate of DE but it has two severe problems like "cosmic coincidence" and "fine tuning" (Peebles 2003). Due to this, it is being avoided for the discussion of DE. As an alternative to this model, many dynamical DE models have been proposed till now, such as quintessence, k-essence and perfect fluid models (Amendola and Tsujikawa 2010). The perfect fluid models possesses the specific form of EoS such as family of Chaplygin gas (Kamenshchik et al. 2001; Bento et al. 2002; Zhang et al. 2006), holographic (Hsu 2004; Li 2004), new agegraphic (Wei and Cai 2008), PDE (Wei 2012; Sharif and Jawad 2013a, 2013b, 2014; Jawad 2014a; Sharif and Rani 2014; Chattopadhyay et al. 2014), QCD ghost DE (in different versions) (Urban and Zhitnitsky 2009a, 2009b, 2010a, 2010b, 2011; Cai et al. 2012; Garcia-Salcedo et al. 2013) etc. These dynamical DE models have been discussed in detail in the reviews (Copeland et al. 2006; Bamba et al. 2012).

In the scenario of Veneziano ghost of chromodynamics (QCD), a dynamical DE called Veneziano ghost DE has been developed. It is suggested that this DE helps in solving the $U(1)$ problem in QCD. This Veneziano ghost gives non-trivial physical effects in FRW universe (Rosenzweig et al. 1980; Nath and Arnowitt 1981). Moreover, QCD ghost (is proportional to $\Lambda^3_{\mathrm{QCD}} H$) has small contribution in realizing the vacuum energy density. Here, $\Lambda_{\mathrm{QCD}} \sim 100$ MeV which is smallest QCD scale. However, this contribution plays crucial role in explaining the evolutionary universe. This DE model has also been used for solving the two severe problems of DE called fine tuning and cosmic coincidence problem (Urban and Zhitnitsky 2009a, 2009b, 2010a, 2010b, 2011; Forbes and Zhitnitsky 2008). This model has also been evaluated through various cosmological parameters theoretically (Ebrahimi and Sheykhi 2011; Sheykhi and Sadegh 2012; Sheykhi and Bagheri 2011; Rozas-Fernandez 2012; Karami and Fahimi 2013a, 2013b) and different observational schemes (Cai et al. 2011).

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Moreover, the Veneziano ghost field in QCD of the form $H + O(H^2)$ can put enough vacuum energy to describe the accelerated expansion of the universe (Zhitnitsky 2012), but only leading term (i.e., H) involved in ordinary ghost DE model. It is pointed out (Cai et al. 2012) that the presence of H^2 in the ordinary ghost DE may be useful in describing the early evolution of the universe called generalized ghost DE. The new version has also been proposed in which it is shown that QCD GDE energy density can be related with the radius of the trapping horizon (Garcia-Salcedo et al. 2013). It is defined as follows

$$\rho_D = \frac{\alpha(1-\epsilon)}{\tilde{r}_T} = \alpha(1-\epsilon)\sqrt{H^2 + \frac{k}{H^2}}, \quad \epsilon \equiv \frac{\dot{\tilde{r}}_T}{2H\tilde{r}_T}. \quad (1)$$

The scalar field models are also used as an alternative to DE such as quintessence, tachyon, K-essence and dilaton. They have also played effective role for DE phenomenon. The dynamics of these scalar field models and the corresponding potential have been widely investigated in the scenario of different DE models such as HDE model with Hubble, future event and Granda-Oliveros IR cutoffs in flat and non-flat universe models (Zhang et al. 2007; Setare 2007; Granda and Oliveros 2009; Karami and Fehri 2010; Zhang 2007; Rozas-Fernández 2010, 2011; Jamil and Farooq 2010; Sheykhi 2011; Jawad and Majeed 2015). They produced interesting results of scalar field and their potential and give useful description about the accelerated expansion of the universe. We have also explored the reconstruction of the scalar field models and interacting HDE with Granda-Oliveros IR cutoff in non-flat universe. We have also provided the comparison with attractor and scaling solutions that exist in these models (Sharif and Jawad 2012).

Moreover, Karami and Abdolmaleki (2012) and Karami et al. (2013) have discussed the dynamics of scalar field and corresponding potential in the presence of viscous ghost as well as generalized ghost DE models in non-flat universe. They also checked the effects of viscus parameter on the dynamics of scalar field and corresponding potential and found interesting results. Recently, Chattopadhyay (2014a, 2014b) has explored reconstruction phenomenon of modified gravities (by using $f(T)$ and $f(G)$ gravities) and DE (modified QCD ghost DE) and found interesting results. We have also reconstructed $f(\tilde{R})$ models in the presence of modified QCD ghost DE (Jawad 2014b). In the present paper, we provide the correspondence of modified QCD ghost DE with scalar field models such as quintessence, tachyon, k-essence and dilaton in flat universe. In the next section, we elaborate basic cosmological scenario and discuss the equation of state (EoS) parameter. Section 3 possesses the discussion of scalar field models. The last section devoted for concluding remarks.

2 Modified QCD ghost dark energy

In this section, we discuss the basic cosmological scenario in the presence of interacting QCD ghost DE with CDM in flat FRW universe. The first Friedmann equation is

$$H^2 = \frac{1}{3M_p^2}(\rho_m + \rho_D), \quad (2)$$

where ρ_m and ρ_D are the energy density of CDM and QCD ghost DE, respectively. By taking into account the interaction between CDM and QCD ghost DE, the continuity equations turn out to be

$$\dot{\rho}_m + 3H\rho_m = Q, \qquad \dot{\rho}_D + 3H\rho_D(1+\omega_D) = -Q, \quad (3)$$

where $\omega_D = \frac{p_D}{\rho_D}$ and Q stand for the equation of state (EoS) parameter and the interaction term, respectively. We choose the interaction as $Q = 3d^2H\rho_m$ and d^2 is a coupling constant. In flat universe, the modified QCD ghost DE takes the form

$$\rho_D = \alpha\left(1 + \frac{\dot{H}}{2H}\right). \quad (4)$$

Its evolution with respect to cosmic time takes the form

$$\dot{\rho}_D = \alpha\dot{H} + \frac{\alpha}{2}\left(\frac{\dot{H}^2 - H\ddot{H}}{H^2}\right). \quad (5)$$

In terms of fractional energy density, Eq. (1) turns out to be

$$\Omega_m + \Omega_D = 1, \qquad \Omega_m = \frac{\rho_m}{3M_p^2H^2}, \qquad \Omega_D = \frac{\rho_D}{3M_p^2H^2}. \quad (6)$$

From Eq. (3) and $Q = 3d^2H\rho_m$, we get

$$\rho_m = \rho_{m_0}a^{3(d^2-1)} \quad (7)$$

where ρ_{m_0} is an integrating constant. Inserting Eqs. (4) and (7) in Eq. (1), we have

$$\frac{dH}{da} = \frac{1}{a}\left(-\frac{2}{\alpha}H_0^2\Omega_{m_0}a^{3(d^2-1)} - \frac{2}{3} + \frac{2}{\alpha}H^2\right). \quad (8)$$

We solve this differential with respect to a and plot it as shown in Fig. 1 with initial condition $H[1] = 74$. It shows increasing behavior with the passage of time which is consistent with the present accelerated expansion of the universe.

After some calculations, we can obtain EoS parameter as

$$\omega_D = -1 - \frac{2H_0^2\Omega_{m_0}d^2Ha^{3(d^2-1)}}{\alpha(2H^2 + \dot{H})} - \frac{2H^2\dot{H} + \dot{H}^2 - H\ddot{H}}{3H^2} \quad (9)$$

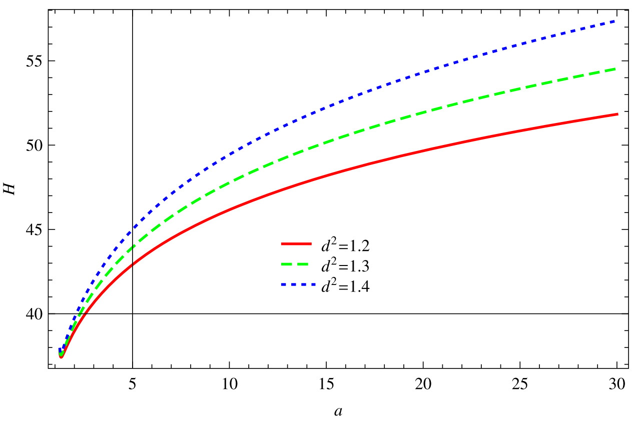

Fig. 1 Plot of $H(a)$ versus a

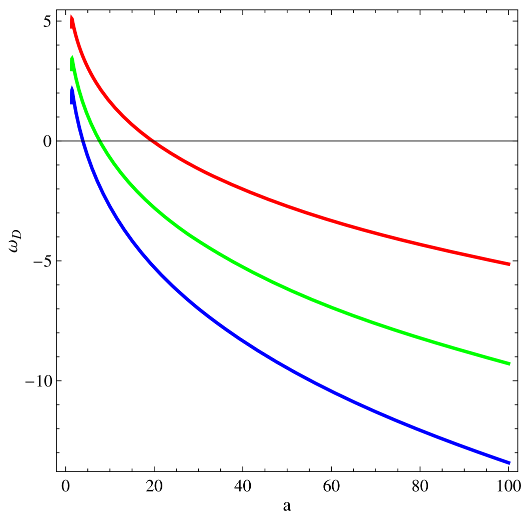

Fig. 2 Plot of ω_D versus a

We have plot ω_D versus a numerically by taking initial value of $H[1] = 74$ as shown in Fig. 2. Also, we assume three values of interaction parameter $d^2 = 1.2, 1.3, 1.4$ and other constant cosmological parameters are $\alpha = 2.21$, $\Omega_{m0} = 0.27$. The EoS parameter translates the universe from matter dominated era towards quintessence and phantom.

3 Reconstruction of scalar field models

In this section, we implement a correspondence between interacting modified QCD ghost DE and various scalar field models.

3.1 Quintessence model

The energy density and pressure of the quintessence scalar field are given by (Copeland et al. 2006)

$$\rho_q = \frac{1}{2}\dot{\phi}^2 + V(\phi), \qquad p_q = \frac{1}{2}\dot{\phi}^2 - V(\phi). \tag{10}$$

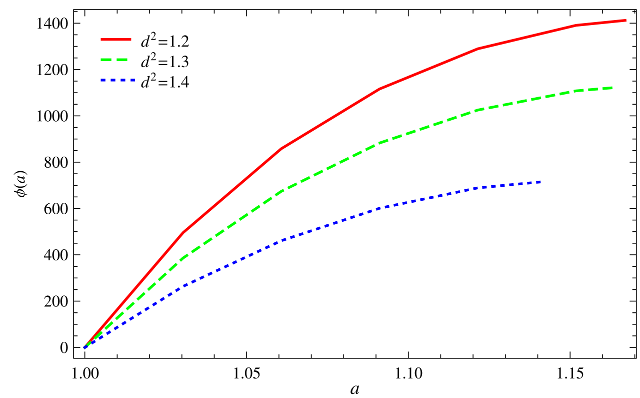

Fig. 3 Plot of $\phi(a)$ versus a in quintessence model

Thus, the potential and the kinetic energy term can be written as

$$V(\phi) = \frac{(1-\omega_\phi)\rho_\phi}{2}, \qquad \dot{\phi}^2 = (1+\omega_\phi)\rho_\phi, \tag{11}$$

where $\omega_\phi = \frac{p_\phi}{\rho_\phi}$. For establishing the correspondence between present DE with quintessence scalar field, we identify $\rho_D = \rho_\phi$ and $\omega_D = \omega_\phi$, one can get

$$\frac{d\phi}{da} = \frac{1}{aH}\sqrt{\left(-\frac{2Hd^2\rho_{m_0}a^{3(d^2-1)}}{\alpha(2H^2+\dot{H})} - \frac{2H^2\dot{H}+\dot{H}^2-H\ddot{H}}{3H^2}\right)\left(\alpha+\frac{\alpha\dot{H}}{2H}\right)}. \tag{12}$$

To identify the behavior of scalar field ϕ, we solve this expression numerically corresponding to a whose output is shown in Fig. 3. It is observed that the scalar field shows increasing behavior and hence the corresponding kinetic energy decreases and approaches to zero with the passage of time. This behavior gives $\omega_q \to -1$ which corresponds to the present observations of the universe. Also, the quintessence potential becomes

$$V(\phi) = \frac{1}{2}\left[2 + \frac{2Hd^2\rho_{m_0}a^{3(d^2-1)}}{\alpha(2H^2+\dot{H})} + \frac{2H^2\dot{H}+\dot{H}^2-H\ddot{H}}{3H^2}\right] \times \left(\alpha + \frac{\alpha\dot{H}}{2H}\right). \tag{13}$$

The quintessence potential versus scalar field ϕ is shown in Fig. 3. The quintessence potential shows rapid increase from very low values and goes towards maximum value. This behaves like an exponential potential which corresponds to cosmological scaling solutions (Copeland et al. 2006). After short interval of time, the potential approaches to zero for all values of d^2 which mimics the stiff matter era of the universe ($\omega_Q = 1$) and corresponds to early universe.

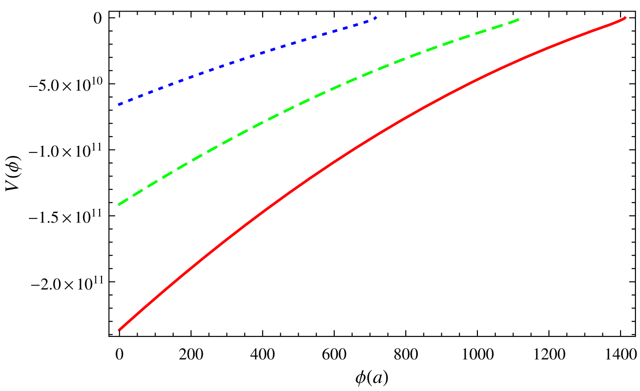

Fig. 4 Plot of $V(\phi)$ versus $\phi(a)$ in quintessence model

3.2 Tachyon model

In this model, the energy density and pressure of tachyon field are defined as follows (Copeland et al. 2006)

$$\rho_t = \frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}, \qquad p_t = -V(\phi)\sqrt{1-\dot{\phi}^2}. \tag{14}$$

The EoS Parameter and potential of tachyon field takes the form

$$\omega_t = \dot{\phi}^2 - 1. \tag{15}$$

Through correspondence scenario of present DE model and tachyon scalar field model, we obtain

$$\frac{d\phi}{da} = \frac{1}{aH}\sqrt{-\frac{2Hd^2\rho_{m_0}a^{3(d^2-1)}}{\alpha(2H^2+\dot{H})} - \frac{2H^2\dot{H}+\dot{H}^2-H\ddot{H}}{3H^2}}. \tag{16}$$

It can be observed from Fig. 5 that tachyon scalar field exhibits the increasing behavior for all values of d^2. This results the decrease of kinetic energy and approaches to zero in the later epoch which mimics the vacuum energy to drive the accelerated expansion of the universe (which can be seen from Eq. (15)). It can also be noted from Eq. (14) that the strong energy condition ($\rho + 3p \geq 0$) becomes $\rho_t + 3p_t = -\frac{2V(\phi)}{\sqrt{1-\dot{\phi}^2}}(1-\frac{3}{2}\dot{\phi}^2)$ which violates for the small values of $\dot{\phi}$ and leads to expansion with acceleration (Copeland et al. 2006). Also, the tachyon potential becomes

$$V(\phi) = \left(\alpha + \frac{\alpha\dot{H}}{2H}\right) \times \sqrt{1 + \frac{2Hd^2\rho_{m_0}a^{3(d^2-1)}}{\alpha(2H^2+\dot{H})} + \frac{2H^2\dot{H}+\dot{H}^2-H\ddot{H}}{3H^2}}. \tag{17}$$

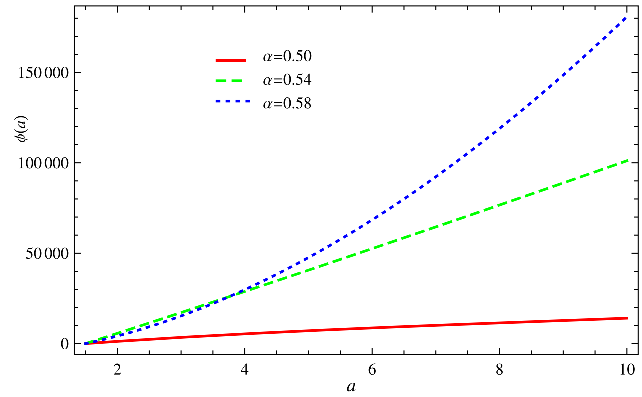

Fig. 5 Plot of $\phi(a)$ versus a for tachyon model

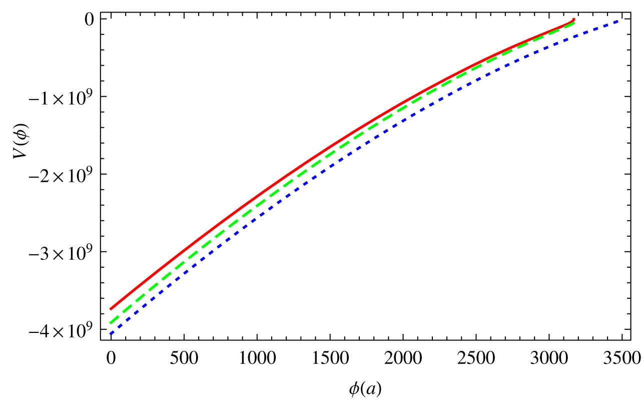

Fig. 6 Plot of $V(\phi)$ versus $\phi(a)$ for tachyon model

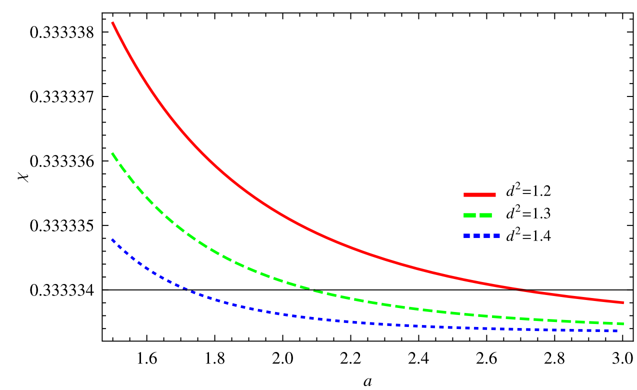

Fig. 7 Plot of X versus a for k-essence model

The tachyon potential against scalar field is shown in Fig. 6. It can be seen that the tachyon potential shows increasing behavior for all values of d^2.

3.3 K-essence model

The energy density and corresponding pressure of k-essence model are of the form (Copeland et al. 2006)

$$\rho_k = V(\phi)\left(-\chi + 3\chi^2\right), \qquad p_k = V(\phi)\left(-\chi + \chi^2\right). \tag{18}$$

where $\chi = \frac{\dot{\phi}^2}{2}$. The EoS parameter has the form

$$\omega_k = \frac{p_k}{\rho_k} = \frac{\chi - 1}{3\chi - 1} \tag{19}$$

in which χ experienced the accelerated expansion of the universe in the interval $(\frac{1}{3}, \frac{2}{3})$. Taking $\omega_k = \omega_D$, we obtain

$$\chi = \big[3\big(-6H^2\alpha\big(2H^2+\dot{H}\big) - 6H^3d^2\rho_{m_0}a^{3(d^2-1)} - \alpha\big(2H^2+\dot{H}\big)\big(2H^2\dot{H}+\dot{H}^2-H\ddot{H}\big)\big)\big] \times \big[-4H^2\alpha\big(2H^2+\dot{H}\big) - 6H^3d^2\rho_{m_0}a^{3(d^2-1)} - \alpha\big(2H^2+\dot{H}\big)\big(2H^2\dot{H}+\dot{H}^2-H\ddot{H}\big)\big].$$

Figure 7 shows that the plot of χ versus a is exactly lies within the range $0.33 < \chi < 0.66$ where the EoS parameter of k-essence model (Eq. (19)) shows consistency with the accelerated universe. Also, $\chi = \frac{1}{2}\dot{\phi}^2$ provides

$$\frac{d\phi}{da} = \frac{1}{aH}\sqrt{\frac{2(-2-d^2\rho_{m_0}a^{3(d^2-1)})(6H^2+3\dot{H}) - (2H^2\dot{H}-\dot{H}^2+H\ddot{H})}{(-4-3-d^2\rho_{m_0}a^{3(d^2-1)})(6H^2+3\dot{H}) - 3(2H^2\dot{H}-\dot{H}^2+H\ddot{H})}}. \tag{20}$$

Figure 8 represents that the field increases steadily. On the other hand, kinetic energy rapidly decreases with the same rate and approaches to zero, i.e., $\chi \to 0$ for which $\omega_k \to 1$. This limit corresponds to stiff matter dominated era of the universe. The k-essence potential takes the form

$$V(\phi) = \big[3\alpha\big(2H^2+\dot{H}\big)\big(-6H^2-2H^2\dot{H}-\dot{H}^2+H\ddot{H}\big) - 18H^3d^2a^{3(d^2-1)} \times \rho_{m_0}\big]\big[2\alpha\big(-25H^2-2H^2\dot{H} + \dot{H}^2 - H\ddot{H}\big)\big(2H^2+\dot{H}\big) - 48H^3d^2\rho_{m_0}a^{3(d^2-1)}\big] \times \big[\alpha\big(2H^2+\dot{H}\big)\big(-4H^2-2H^2\dot{H}-\dot{H}^2+H\ddot{H}\big) - 6H^3d^2\rho_{m_0}a^{3(d^2-1)}\big]^{-2}.$$

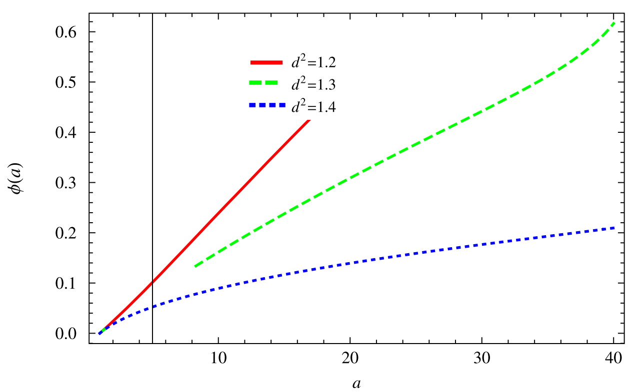

Fig. 8 Plot of $\phi(a)$ versus a for k-essence model

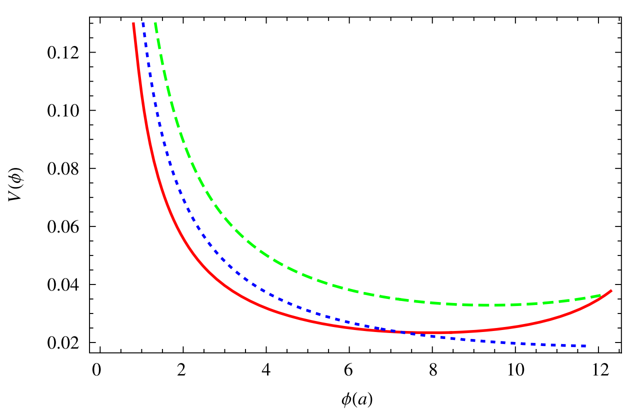

Fig. 9 Plot of $V(a)$ versus $\phi(a)$ for k-essence model

The above k-essence potential can be plotted against $\phi(a)$ as shown in Fig. 9. It shows oscillating behavior, i.e., it shows sharp increasing behavior at the beginning and then attains the maximum value and then sharply decreases and approaches to zero.

3.4 Dilaton field

The pressure and energy density in this model are (Copeland et al. 2006)

$$p_d = -\chi + \beta\chi^2e^{\lambda\phi}, \qquad \rho_d = -\chi + 3\beta\chi^2e^{\lambda\phi}. \tag{21}$$

Here λ and β appear as positive constants. The EoS parameter becomes

$$\omega_d = \frac{1-\alpha e^{\lambda\phi}\chi^2}{1-3\alpha e^{\lambda\phi}\chi^2}. \tag{22}$$

To establish the correspondence between modified QCD ghost DE and dilaton field, we equate their EoS parameters, i.e. $\omega_d = \omega_D$, which gives

$$\chi e^{\lambda\phi} = \frac{1-\omega_D}{\beta(1-3\omega_D)}. \tag{23}$$

The plot of $\chi e^{\lambda\phi}$ versus a with $\lambda = 0.5 = \beta$ is shown in Fig. 10. It can be observed that the kinetic energy term $e^{\lambda\phi}\chi$ of dilaton scalar field lies in the interval (0.66, 1.33). However, EoS parameter ω_D predicts the accelerated expansion of the universe in the interval (0.66, 1.33). Hence, modified

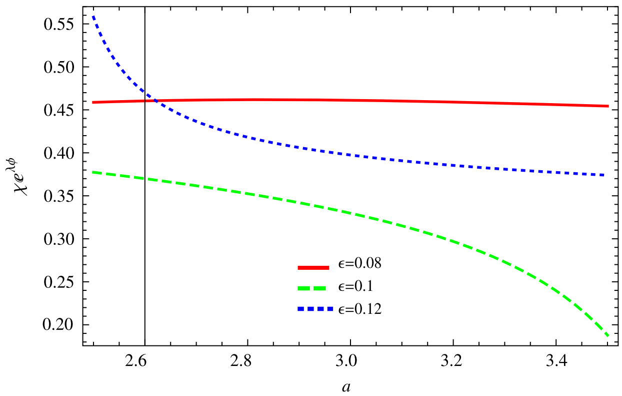

Fig. 10 Plot of $\chi e^{\lambda\phi}$ versus a in dilaton model

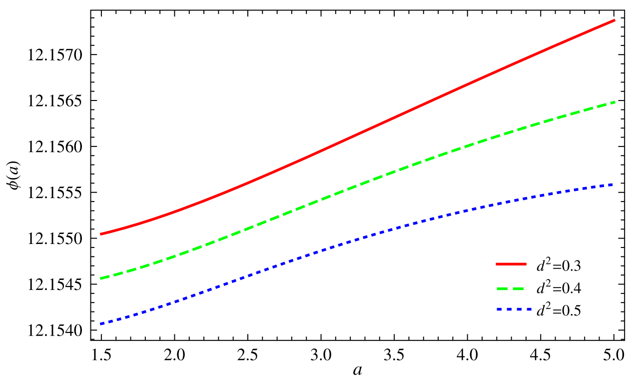

Fig. 11 Plot of $\phi(a)$ versus a for dilaton model

QCD DE version of dilaton field is consistent with present observations of the universe. By using $\chi = \frac{\dot{\phi}^2}{2}$, one can get

$$\phi = \frac{2}{\lambda}\ln\Bigg(1 + \int\Bigg[\frac{\lambda}{2aH}\big(2\big(6H^2\alpha\big(2H^2+\dot{H}\big) + 6H^3H_0^2\Omega_{m_0}d^2\rho_{m_0}a^{3(d^2-1)} + \alpha\big(2H^2\dot{H}+\dot{H}^2-H\ddot{H}\big)\big(2H^2+\dot{H}\big)\big)\big)\Bigg]^{\frac{1}{2}} \times \big[3\beta\big(-4H^2\alpha\big(2H^2+\dot{H}\big) - H^3 6d^2H_0^2\Omega_{m_0}\rho_{m_0}a^{3(d^2-1)} - \beta\big(2H^2\dot{H}+\dot{H}^2-H\ddot{H}\big)\big(2H^2+\dot{H}\big)\big)\big]^{-\frac{1}{2}}da\Bigg).$$

We can observe that dilaton field shows increasing behavior with the passage of time for all values of d^2 (Fig. 11).

4 Concluding remarks

In this work, we have considered interacting modified ghost DE with CDM in the flat FRW universe. We have developed Hubble and EoS parameters by considering three distinct cases of d^2. The Hubble parameter exhibits the increasing behavior which is consistence with the present day observations (Fig. 1). Also, the EoS parameter shows translation from matter dominated era and goes towards phantom region by crossing the phantom divide line (Fig. 2). We have given the correspondence of the present DE model with scalar field models such as quintessence, tachyon, k-essence and dilaton models.

In quintessence model, scalar field shows increasing behavior and hence the corresponding kinetic energy decreases and approaches to zero with the passage of time (Fig. 3). This behavior gives $\omega_q \to -1$ and corresponds to the present observations of the universe. The quintessence potential versus scalar field ϕ is shown in Fig. 4. The quintessence potential shows rapid increase from very low values and goes towards maximum value. This behaves like an exponential potential which corresponds to cosmological scaling solutions (Copeland et al. 2006). After short interval of time, the potential approaches to zero for all values of d^2 which mimics the stiff matter era of the universe ($\omega_Q = 1$) and corresponds to early universe. Figure 5 have shown that tachyon scalar field exhibits the increasing behavior for all values of d^2. This results the decrease of kinetic energy and approaches to zero in the later epoch which mimics the vacuum energy to drive the accelerated expansion of the universe (which can be seen from Eq. (15)). The tachyon potential against scalar field is shown in Fig. 6. It can be seen that the tachyon potential shows increasing behavior for all values of d^2.

In Fig. 7, we can see that χ exactly lies within the range $0.33 < \chi < 0.66$ where the EoS parameter of k-essence model (Eq. (19)) shows consistency with the accelerated universe. Figure 8 represents that the field increases steadily. On the other hand, kinetic energy rapidly decreases with the same rate and approaches to zero, i.e., $\chi \to 0$ for which $\omega_k \to 1$. This limit corresponds to stiff matter dominated era of the universe. The above K-essence potential can be plotted against $\phi(a)$ as shown in Fig. 9. It shows oscillating behavior, i.e., it shows sharp increasing behavior at the beginning and then attains the maximum value and then sharply decreases and approaches to zero. Figure 10 represents that the kinetic energy term $e^{b_2\phi}\chi$ of dilaton scalar field lies in the interval (0.66, 1.33). However, EoS parameter ω_D predicts the accelerated expansion of the universe in the interval (0.66, 1.33). Hence, modified QCD DE version of dilaton field is consistent with present observations of the universe. We can observe that dilaton field shows increasing behavior with the passage of time for all values of d^2 (Fig. 11).

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